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Biomass of Antarctic krill in the Scotia Sea in January/February 2000 and its use in revising an estimate of precautionary yield

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Abstract

In January and February 2000, a collaborative survey designed to assess the biomass of Antarctic krill across the Scotia Sea was conducted aboard research vessels from Japan, Russia, the UK and the USA using active acoustic and net sampling. Survey design, sampling protocols, and data analysis procedures are described. Mean krill density across the survey area was estimated to be $21.4\,\mathrm{g\,m^{-2}}$, and total biomass was estimated to be 44.3 million tonnes (CV 11.4%). This biomass estimate leads to a revised estimate of precautionary yield for krill in the Scotia Sea of 4 million tonnes. However, before the fishery can be permitted to expand to this level, it will be necessary to establish mechanisms to avoid concentration of fishing effort, particularly near colonies of land-breeding krill predators, and to consider the effects of krill immigrating into the region from multiple sources.
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1. Introduction

The highest concentrations of Antarctic krill (*Euphausia superba*), krill predators, and krill-fishing effort in the Southern Ocean are located in the Scotia Sea (Agnew and Nicol, 1996; Laws, 1985; Marr, 1962). The international fishery is regulated in accordance with the Convention for the Conservation of Antarctic Marine Living Resources, which is part of the Antarctic Treaty system. In principle, the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) has adopted a feedback approach to management of the krill fishery, by which management measures are adjusted in response to ecosystem monitoring (Constable et al., 2000; Hewitt and Linen Low, 2000). However, such a scheme remains to be fully developed. In the interim, a complementary approach, which defines and implements provisions of Article II[2] of the Convention in reference to the Scotia Sea krill stock, was adopted in order to set a precautionary catch limit (Butterworth et al., 1991, 1994).

The approach is to set the proportion (γ) of unexploited population biomass (B_0) that can be harvested under defined management criteria. The allowable catch, referred to as the precautionary yield (Y), is thus defined as

$$Y = \gamma B_0. \tag{1}$$

The risks of exceeding the criteria are evaluated by comparing statistical distributions of population biomasses generated from simulated population trajectories, with and without fishing mortality. Uncertainty is accommodated by using values of abundance, recruitment, growth, and mortality drawn from appropriate statistical distributions. The first criterion is to protect the viability of the harvested population and for Antarctic krill is defined such that the probability that the spawning biomass declines to less than 20% of its unexploited median level during any one year should be less than 10%. The second criterion is to protect the viability of krill predator populations; this is defined such that the median population level should be at least 75% of the unexploited median population level. The third criterion is to evaluate these risks using population trajectories that extend at least 20 years. The value of the harvest rate, expressed as a proportion of the unexploited biomass (γ), that meets these criteria is accepted as the most precautionary. This value, together with an estimate of B_0, is used to set the precautionary yield for krill.

Two important parameters in this analysis are B_0 and its associated variance. These values are used to generate a distribution of population biomasses from which an initial biomass is drawn for each population trajectory. Initially, an estimate of krill biomass was generated from acoustic data collected during the first international BIOMASS experiment (FIBEX)[3] in 1981 (Trathan et al., 1992), the only large-scale acoustic survey in this region prior to 2000. Because exploitation had historically been low relative to the size of the fished resource an estimate of the standing stock was assumed to approximate B_0. Recent reports of the Scientific Committee of CCAMLR have questioned the current relevance of this estimate (e.g. CCAMLR, 1995, Annex 4, para 4.61) and have recommended a new survey.

The reasons for conducting a new survey were recognition that: (1) several technical improvements had been made in the assessment of krill biomass using active acoustic methods since the FIBEX survey (Everson et al., 1990; Greene et al., 1991; Hewitt and Demer, 1991); (2) the FIBEX survey area was substantially less than the known habitat of krill in the Scotia Sea (CCAMLR, 1995); and (3) the krill population in the Scotia Sea may not be stable. Recently, published evidence suggests that krill reproductive success may be dependent on multi-year changes in the physical environment (Brierley et al., 1999; Loeb et al.,

[2]Article II of the Convention mandates that fisheries be managed such that: (a) the size of harvested populations is sufficient to ensure stable recruitment; (b) ecological relationships between harvested and dependent populations are maintained; and (c) changes to the marine system that cannot be reversed over two to three decades are prevented.

[3]In the early 1980s, the Scientific Committee for Antarctic Research (SCAR) established the BIOMASS Program (Biological Investigations of Antarctic Systems and Stocks). FIBEX was a multi-national, multi-ship effort to conduct large-scale acoustic surveys over large areas of the Southern Ocean. See also El-Sayed (1994).

1997; Naganobu et al., 1999; Nicol et al., 2000; White and Peterson, 1996). During periods of northward excursions of the Southern Boundary of the Antarctic Circumpolar Current (SBACC), the development of winter sea ice is more extensive, populations of *Salpa thompsoni* (a pelagic tunicate postulated to be a competitor with krill for access to the spring phytoplankton bloom) are displaced offshore, and both krill reproductive output and survival of their larvae are enhanced. During periods of southward excursion of the SBACC, the development of winter sea ice is less extensive, salps are more abundant closer to shore, and krill reproductive success is depressed. These interactions may be confounded by a warming trend observed in the region of the Antarctic Peninsula over the last 50 years (Vaughan and Doake, 1996). The intention was to anchor the estimate of precautionary yield with the most recent and accurate assessment of Antarctic krill in the Scotia Sea possible. Because harvest rates continue to be low relative to the size of the fished resource, it was again assumed that an estimate of the current standing stock was equivalent to B_0.

Plans for the survey developed over a period of 5 years through a series of working papers, discussions at the meetings of the Scientific Committee of CCAMLR and its working groups, and more formal workshops (CCAMLR, 1995, Annex 4, paras 4.62–4.67; CCAMLR, 1996, Annex 4, paras 3.72–3.75; CCAMLR, 1997, Annex 4, paras 8.121–8.129; CCAMLR, 1998, Annex 4, paras 9.49–9.90; CCAMLR, 1999, Annex 4, paras 8.1–8.74 and Appendix D). The final survey design and protocols for data collection were adopted by consensus and are described by Trathan et al. (2001) and Watkins et al. (2004).

The survey was conducted during January and February 2000 using the R./V. *Kaiyo Maru* (Japan), the R./V. *Atlantida* (Russia), the RRS *James Clark Ross* (UK), and the R./V. *Yuzhmorgeologiya* (a Russian research vessel under charter to the US) (Table 1). A 2-week workshop was held in May/June 2000 to process the acoustic data and to estimate B_0 and its associated variance (CCAMLR, 2000a, Annex 4, Appendix G). CCAMLR subsequently adopted a revised precautionary catch limit for krill (CCAMLR, 2000b; Hewitt et al., 2002). Much of the information presented here is drawn from these reports.

2. Survey design and data collection protocols

The defining physical feature of the Scotia Sea is its southern boundary along the Scotia Ridge, extending from the South Shetland Islands east and north through the South Orkney Islands, the South Sandwich Islands, and South Georgia (Fig. 1). This ridge influences the direction and intensity of the ACC. Antarctic krill appear to move eastward through the Scotia Sea via the ACC, although the relative importance of passive transport versus active migration is uncertain. Likely sources of immigrants to the Scotia Sea are the Bellingshausen Sea to the west and the Weddell Sea to the south. Differences in mitochondrial DNA sequences suggest that krill from these regions may be genetically distinct (Zane et al., 1998). Within the Scotia Sea, zones of water convergence, eddies, and gyres are loci for krill concentrations (Makarov et al., 1988; Witek et al., 1988). Krill spawn in the vicinity of the South Shetland and South Orkney Islands. Although they are abundant further to the north and east near South Georgia, they do not spawn there in great numbers and few larvae are found (Fraser, 1936; Siegel, 2000). Consumption of krill throughout the Scotia Sea by baleen whales, crabeater and fur seals, pygoscelid penguins and other seabirds, squid and fish is estimated to be between 16 and 32 million tonnes per year (Everson and de la Mare, 1996). Although higher in previous years, annual harvests of krill since 1992 have averaged approximately 100,000 tonnes.[4] Fishing effort has been concentrated near the shelf breaks along the north side of the South Shetland, South Orkney, and South Georgia archipelagos (Agnew and Nicol, 1996).

[4]Harvest statistics for Antarctic krill are maintained by the CCAMLR Secretariat, P.O. Box 213, North Hobart 7002, Tasmania, Australia. E-mail: ccamlr@ccamlr.org; website: www.ccamlr.org.

Table 1
Summary of survey and calibration activities undertaken by vessels during the CCAMLR, 2000 Survey

	Atlantida	*Kaiyo Maru*	*James Clark Ross*	*Yuzhmorgeologiya*
Survey				
Survey strata	ESS, Sand	AP, SS, SSI	AP, SS	AP, SS, SG, SOI
CCAMLR subareas	48.4	48.1, 48.2, 48.3	48.1, 48.2, 48.3	48.1, 48.2, 48.3
Start date	17 January	11 January	18 January	13 January
End date	1 February	2 February	10 February	4 February
Number of large-scale transects	3	6	7	6
Transect names	SSA SSB SSC	SS03 SS06 SS09 AP12 AP15 AP18	AP13 AP16 AP19 SS01 SS04 SS07 SS10	AP11 AP14 AP17 SS02 SS05 SS08
Number of mesoscale transects	10	8	0	8
Transect names	Sand01-10	SSI01-08		SG01-04 SOI01-04
Calibration				
Pre-survey				
Date	14 January	9 January	16 January	12 January
Location	Stromness Bay	Stromness Bay	Stromness Bay	Stromness Bay
Post-survey				
Date	5 February	4 February	11 February	7 March
Location	Stromness Bay	Admiralty Bay	Admiralty Bay	Admiralty Bay

Large-scale strata: AP—Antarctic Peninsula, SS—Scotia Sea, ESS—Eastern Scotia Sea. Mesoscale strata: SSI—South Shetland Islands, SOI—South Orkney Islands, SG—South Georgia, Sand—South Sandwich Islands.

The survey area extended across the Scotia Sea and included the continental shelves, oceanic regions; the major frontal zones associated with the ACC, and the principal areas of fishing activity (Fig. 1A). The survey design consisted of seven strata (four large-scale strata and three mesoscale strata, Fig. 1B) with randomly spaced parallel transects within each stratum (Trathan et al., 2001). The mean density on a transect within a stratum, as determined from acoustic sampling of krill, was considered to be a representative sample of the mean density of the stratum (Jolly and Hampton, 1990). Each vessel also obtained net samples and profiles of oceanographic parameters on stations conducted near local apparent noon and mid-night each day of the survey.

All ships collected active acoustic data using Simrad EK500 echosounders (with firmware version 5.3, modified to generate 1 ms pulse duration for 200 kHz) connected to hull-mounted 38, 120, and 200 kHz transceivers. The majority of transceiver settings were specified by the agreed data collection protocols (Watkins et al., 2004), Table 2 lists important transceiver and transducer specifics for each ship. Samples of volume backscattering strength (S_V) were collected every 0.71 m from each of the transducer faces to 500 m below the surface. Pings were fired simultaneously on all frequencies and the interval between pings was 2 s. Pulse duration for all three frequencies was 1 ms. Data output telegrams from the EK500 echosounder were logged using SonarData's EchoLog software. Although acoustic data were logged on all ships continuously throughout the survey, transect data were only collected between the hours of local apparent sunrise and sunset. Nominal vessel speed was set at 10 kn. See Watkins et al. (2004) for additional details regarding the acoustic sampling protocols.

Acoustic system calibrations were undertaken before and after the survey. Initial calibrations were conducted in Stromness Bay, South Georgia, final calibrations in Stromness Bay (*Atlantida*) or Admiralty Bay, King George Island (*James Clark Ross*, *Kaiyo Maru*, and *Yuzhmorgeologiya*). All calibrations were undertaken using the standard

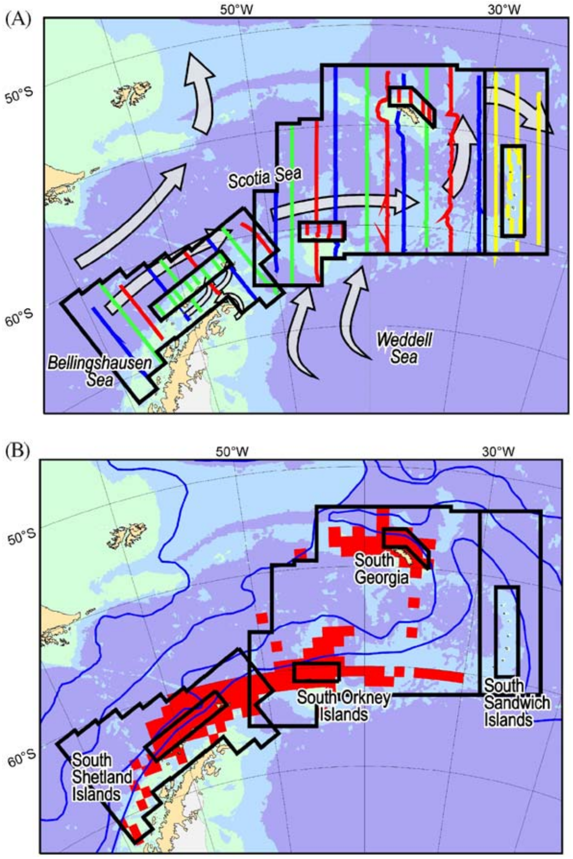

Fig. 1. Island groups and bathymetry of the Scotia Sea (shading indicates 500, 1000 and 3000 m isobaths), reproduced from Hewitt et al. (2002): (A) Survey strata outlined in black relative to historical fishing activity (red squares) and major ocean frontal zones (blue lines; from north to south, the Subantarctic Front, the Polar Front, the Southern Antarctic Circumpolar Current Front, and the Southern Boundary of the Antarctic Circumpolar Current). (B) Survey transects color coded; green indicates those occupied by the *Kaiyo Maru*, yellow *Atlantida*, blue *James Clark Ross*, and red *Yuzhmorgeologiya*. Arrows indicate direction of major currents.

sphere method (Foote, 1990; Foote et al., 1987). The primary calibration spheres were 38.1 mm diameter tungsten carbide spheres from the same manufacturing lot, bored and fitted with monofilament loops; copper spheres of 60.0, 23.0, and 13.7 mm diameter also were used. Temperature and salinity at the calibration sites were similar and within the range of the major portion of the CCAMLR, 2000 Survey area. In two instances inclement weather slightly prejudiced the quality of the results. For the *Atlantida* the second calibration, and for the *Kaiyo Maru* the first calibration, were considered to be the better of the two. For the *Yuzhmorgeologiya* and the *James Clark Ross* the mean values of the two calibrations were used. Calibration specifics for each ship are listed in Table 3 (see also CCAMLR, 2000a, Annex 4, Appendix G Tables 8–11).

Krill were directly sampled using a Rectangular Midwater Trawl with an 8 m^2 mouth opening (RMT-8; Baker et al., 1973) near local apparent noon and mid-night each day. The RMT-8 was fished obliquely down to 200 m and up to the surface. Standard lengths and maturity stages were determined for every krill if the catch was less than 100 animals or a subsample of at least 100 animals if the catch was larger. See Watkins et al. (2004) and Siegel et al. (2004) for additional details regarding net sampling protocols.

3. Data processing methods

Echograms were assembled from the ping-by-ping acoustic data and annotated; during this process some parameters set in the echosounders during data collection were adjusted. Prior to the survey, historical profiles of seawater temperature and salinity across the Scotia Sea were examined. Averages, weighted in favour of those depths where krill were most often observed, were calculated and the corresponding sound velocity determined as 1449 m s^{-1}. Examination of profiles obtained during the survey indicated that a value of 1456 m s^{-1} would be more appropriate. Although this change had a very minor effect, the data were processed using the new value. Absorption coefficients were set to 0.010 dB m^{-1} for the 38 kHz data, 0.028 dB m^{-1} for the 120 kHz data, and 0.041 dB m^{-1} for the 200 kHz data (Francois and Garrison, 1982). The nominal resonant frequency of the transducers was used to set the wavelengths at 0.03844 m for the 38 kHz data, 0.01223 m for the 120 kHz data, and 0.00728 m for the 200 kHz data. The equivalent two-way beam angle for each transducer, as provided by the manufacturer for a nominal sound

Table 2
Ship-specific transducer specifications and transceiver settings during data collection

Transceiver specification/setting	*Atlantida*	*James Clark Ross*	*Kaiyo Maru*	*Yuzhmorgeologiya*
(1) (38 kHz, split beam)				
Transducer type	ES38B	ES38B	ES38B	ES38-12
Transducer depth (m)	5.0	5.7	5.8	7.0
Transmitted power (W)	2000	2000	2000	1000
Pulse length (ms)	1.0	1.0	1.0	1.0
Absorption coefficient ($dB\,m^{-1}$)	0.010	0.010	0.010	0.010
Sound speed ($m\,s^{-1}$)	1449 (1456)	1449 (1456)	1449 (1456)	1485 (1456)
Wavelength (m)	0.03868 (0.03844)	0.03868 (0.03844)	0.03868 (0.03844)	0.03868 (0.03844)
Two-way beam angle (dB)	−21.2	−20.8	−20.9	−15.9
S_v transducer gain (dB)	23.43 (23.32)	25.49 (25.51)	27.06	22.43 (22.36)
TS transducer gain (dB)	23.76 (23.50)	25.60	27.32	22.64 (22.51)
Angle sensitivity alongship	21.9	21.9	21.9	12.5
Angle sensitivity athwartship	21.9	21.9	21.9	12.5
3 dB beamwidth alongship (°)	7.1	7.0	6.8	12.2
3 dB beamwidth athwartship (°)	7.1	7.1	6.9	12.2
(2) (120 kHz, split beam)				
Transducer type	ES120-7	ES120	ES120-7	ES120-7
Transducer depth (m)	5.0	5.70	5.8	7.0
Transmitted power (W)	1000	1000	1000	1000
Pulse length (ms)	1.0	1.0	1.0	1.0
Absorption coefficient ($dB\,m^{-1}$)	0.026 (0.028)	0.026 (0.028)	0.026 (0.028)	0.026 (0.028)
Sound speed ($m\,s^{-1}$)	1449 (1456)	1449 (1456)	1449 (1456)	1485 (1456)
Wavelength (m)	0.01225 (0.01223)	0.01225 (0.01223)	0.01225 (0.01223)	0.01225 (0.01223)
Two-way beam angle (dB)	−20.9	−18.4	−20.6	−20.4
S_v transducer gain (dB)	23.23 (24.49)	20.26 (20.20)	24.74	25.37 (25.26)
TS transducer gain (dB)	23.29 (24.66)	20.26 (20.18)	24.83	25.56 (25.37)
Angle sensitivity alongship	15.7	15.7	21.0	21.0
Angle sensitivity athwartship	15.7	15.7	21.0	21.0
3 dB beamwidth alongship (°)	7.3	9.3	7.1	7.3
3 dB beamwidth athwartship (°)	7.3	9.3	7.1	7.3
(3) (200 kHz, single beam)				
Transducer type	200_28	200_28	200_28	200_28
Transducer depth (m)	5.0	5.70	5.8	7.0
Transmitted power (W)	1000	1000	1000	1000
Pulse length (ms)	1.0	1.0	1.0	1.0
Absorption coefficient ($dB\,m^{-1}$)	0.040 (0.041)	0.040 (0.041)	0.040 (0.041)	0.040 (0.041)
Sound speed ($m\,s^{-1}$)	1449 (1456)	1449 (1456)	1449 (1456)	1485 (1456)
Wavelength (m)	0.00735 (0.00728)	0.00735 (0.00728)	0.00735 (0.00728)	0.00735 (0.00728)
Two-way beam angle (dB)	−20.3	−20.8	−20.5	−20.5
S_v transducer gain (dB)	24.83 (23.26)	22.78 (22.91)	25.76	26.12 (25.96)
TS transducer gain (dB)	24.50 (23.47)	23.07 (23.12)	25.78	26.12 (25.96)
3 dB beamwidth alongship (°)	7.1	6.9	7.1	7.1
3 dB beamwidth athwartship (°)	7.1	7.1	7.1	7.1

Values in parentheses indicate adjusted values used during data processing.

speed of 1473 $m\,s^{-1}$, was adjusted for a sound velocity of 1449 $m\,s^{-1}$ prior to data collection aboard the *James Clark Ross* and the *Atlantida* and used during CCAMLR, 2000 Survey. No such adjustments were made for data collected aboard the *Kaiyo Maru* and the *Yuzhmorgeologiya*.

Based on previous experience a surface exclusion layer of 15 m was applied to data from the

Table 3
Calibration specifics for each ship

	First calibration	Second calibration	First calibration	Second calibration	First calibration	Second calibration
Atlantida						
Date	13-Jan-00	05-Feb-00	13-Jan-00	05-Feb-00	13-Jan-00	05-Feb-00
Location	Stromness Bay	Stromness Bay	Stromness Bay	Stromness Bay	Stromness Bay	Stromness Bay
Transducer	ES38B	ES38B	ES120-7	ES120-7	200_28	200_28
Water depth (m)	56	53	54	53	54	53
Sound speed ($m\,s^{-1}$)	1457	1460	1457	1460	1457	1460
Alpha ($dB\,km^{-1}$)	10	10	28	28	41	41
Transmit power (W)	2000	2000	1000	1000	1000	1000
Pulse duration ($m\,s^{-1}$)	1	1	1	1	1	1
Bandwidth (kHz)	3.8 (10%)	3.8 (10%)	1.2 (1%)	1.2 (1%)	2.0 (1%)	2.0 (1%)
2-way beam angle (dB)	−21.2	−21.2	−20.9	−20.9	−20.3	−20.3
Sphere type	60.0 mm CU	38.1 mm WC	23.0 mm CU	38.1 mm WC	13.7 mm CU	38.1 mm WC
Range to sphere (m)	17.1	14.5	15.0	15.9	14.7	15.5
Calibrated S_v gain (dB)	23.43	23.32	23.23	24.49	24.83	23.26
Selected S_v gain (dB)		23.32		24.49		23.26
Calibrated TS gain (dB)	23.76	23.50	23.29	24.66	24.50	23.47
Selected TS gain (dB)		23.50		24.66		23.47
James Clark Ross						
Date	16-Jan-00	12-Feb-00	16-Jan-00	12-Feb-00	16-Jan-00	12-Feb-00
Location	Stromness Bay	Admiralty Bay	Stromness Bay	Admiralty Bay	Stromness Bay	Admiralty Bay
Transducer	ES38B	ES38B	ES120	ES120	200_28	200_28
Water depth (m)	54	264	54	264	54	264
Sound speed ($m\,s^{-1}$)	1458	1455	1458	1455	1458	1455
Alpha ($dB\,km^{-1}$)	10	10	27	27	41	41
Transmit power (W)	2000	2000	1000	1000	1000	1000
Pulse duration ($m\,s^{-1}$)	1	1	1	1	1	1
Bandwidth (kHz)	3.8 (10%)	3.8 (10%)	1.2 (1%)	1.2 (1%)	2.0 (1%)	2.0 (1%)
2-way beam angle (dB)	−20.8	−20.8	−18.4	−18.4	−20.8	−20.8
Sphere type	38.1 mm WC	38.1 mm WC	38.1 mm WC	38.1 mm WC	38.1 mm WC	38.1 mm WC
Range to sphere (m)	27.7	29.9	28.2	29.73	28.2	28.7
Calibrated S_v gain (dB)	25.49	25.53	20.26	20.09	22.78	23.04
Selected S_v gain (dB)		25.51		20.20		22.91
Calibrated TS gain (dB)	25.60	25.60	20.26	20.15	23.07	23.16
Selected TS gain (dB)		25.60		20.18		23.12
Kaiyo Maru						
Date	09-Jan-00	04-Feb-00	09-Jan-00	04-Feb-00	09-Jan-00	04-Feb-00
Location	Stromness Bay	Admiralty Bay	Stromness Bay	Admiralty Bay	Stromness Bay	Admiralty Bay
Transducer	ES38B	ES38B	ES120-7	ES120-7	200_28	200_28
Water depth (m)	80	58	80	58	80	58
Sound speed ($m\,s^{-1}$)	1453	1453	1453	1453	1453	1453
Alpha ($dB\,km^{-1}$)	10	10	28	27	41	40.5
Transmit power (W)	2000	2000	1000	1000	1000	1000
Pulse duration ($m\,s^{-1}$)	1	1	1	1	1	1
Bandwidth (kHz)	3.8 (10%)	3.8 (10%)	1.2 (1%)	1.2 (1%)	2.0 (1%)	2.0 (1%)
Two-way beam angle (dB)	−20.9	−20.9	−20.6	−20.6	−20.5	−20.5
Sphere type	38.1 mm WC	38.1 mm WC	38.1 mm WC	38.1 mm WC	38.1 mm WC	38.1 mm WC
Range to sphere (m)	30.6	30.0	30.0	29.9	30.5	30.1
Calibrated S_v gain (dB)	27.06	27.09	24.74	24.30	25.76	25.74
Selected S_v gain (dB)		27.06		24.74		25.76
Calibrated TS gain (dB)	27.32	27.35	24.83	24.55	25.78	25.77
Selected TS gain (dB)		27.32		24.83		25.78

Table 3 (*continued*)

	First calibration	Second calibration	First calibration	Second calibration	First calibration	Second calibration
Yuzhmorgeologiya						
Date	12-Jan-00	07-Mar-00	12-Jan-00	07-Mar-00	12-Jan-00	07-Mar-00
Location	Stromness Bay	Admiralty Bay	Stromness Bay	Admiralty Bay	Stromness Bay	Admiralty Bay
Transducer	ES38-12	ES38-12	ES120-7	ES120-7	200_28	200_28
Water depth (m)	88	75	88	75	88	75
Sound speed ($m\,s^{-1}$)	1450	1450	1450	1450	1450	1450
Alpha ($dB\,km^{-1}$)	10	10	26	26	40	40
Transmit power (W)	1000	1000	1000	1000	1000	1000
Pulse duration ($m\,s^{-1}$)	1	1	1	1	1	1
Bandwidth (kHz)	3.8 (10%)	3.8 (10%)	1.2 (1%)	1.2 (1%)	2.0 (1%)	2.0 (1%)
2-way beam angle (dB)	−15.9	−15.9	−20.4	−20.4	−20.5	−20.5
Sphere type	38.1 mm WC	38.1 mm WC	38.1 mm WC	38.1 mm WC	38.1 mm WC	38.1 mm WC
Range to sphere (m)	30.0	38.0	29.2	37.6	29.0	37.6
Calibrated S_v gain (dB)	22.43	22.29	25.37	25.16	26.12	25.80
Selected S_v gain (dB)		22.36		25.26		25.96
Calibrated TS gain (dB)	22.64	22.37	25.56	25.17	26.12	25.80
Selected TS gain (dB)		22.51		25.37		25.96

Yuzhmorgeologiya and *Atlantida*, and 20 m for data from the *James Clark Ross* and *Kaiyo Maru*. Because krill may occur near the surface, even during daylight hours, reconstructed echograms were reviewed and adjustments were made to include near-surface biological scatter or to exclude surface noise spikes. This was carried out by a combination of changing the overall depth of the surface exclusion layer or editing small fragments of the surface exclusion layer around individual targets. Table 4 lists surface exclusion layer depths for each transect by ship. Bottom, as detected by the echosounder, was visually verified from the re-constructed echograms and adjusted, if necessary, to ensure that bottom echoes were excluded from the integrated layer. The lower vertical limit of integration was set to 500 or 2 m above the detected bottom where shallower.

No adjustment for noise was made during data collection (i.e. Noise Margin was set to zero under the EK500 Operation Menu). During data processing, time-varied volume backscattering strength due to noise was estimated and subtracted from the echograms (Watkins and Brierley, 1995). Initial estimates of noise were made for each transect and frequency during the survey and used to generate time-varied echograms of noise only. These were visually compared with echograms made with the original data using similar values for the absorption coefficients and the display thresholds for S_V. Noise levels were adjusted until the effects of noise at long ranges appeared equal on each display; another 2 dB was then added in order to arrive at a conservative adjustment for noise. The final values used are listed in Table 4.

Regions of the reconstructed echograms were attributed to krill when the difference in mean volume backscattering strength at 120 and 38 kHz was greater than 2 dB and less than 16 dB (Watkins and Brierley, 2002). Comparisons of single samples of S_V were too variable to allow contiguous regions of the echograms to be delineated as krill. It was therefore necessary to average S_V over bins of finite vertical and horizontal dimension. It was expected that the size of the bins would necessitate a trade-off. If they were too small, the variability between S_V samples would cause the continuous nature of krill swarms and layers apparent on the echograms to be lost. If the bins were too large, the power to delineate krill was diminished because backscatter from both krill and non-krill scatterers would be

Table 4
Surface exclusion layer depths and noise levels (dB) for each transect by ship

Ship	Transect	Surface layer (m)	Noise (S_v re 1 m)		
			38 kHz	120 kHz	200 kHz
Yuz	SG01	20	−123.00	−123.00	−123.00
Yuz	SG02	20	−124.00	−120.00	−121.00
Yuz	SG03	20	−125.00	−124.00	−124.00
Yuz	SG04	15	−137.00	−129.00	−124.00
Yuz	SS02	20	−137.00	−123.00	−124.00
Yuz	SS05	15	−135.00	−125.00	−123.00
Yuz	SS08	15	−131.00	−125.00	−123.00
Yuz	SOI01	15	−126.00	−120.00	−119.00
Yuz	SOI02	15	−126.00	−122.00	−123.00
Yuz	SOI03	15	−129.00	−122.00	−122.00
Yuz	SOI04	20	−135.00	−127.00	−122.00
Yuz	AP11	20	−129.00	−120.00	−123.00
Yuz	AP14	15	−129.00	−120.00	−125.00
Yuz	AP17	20	−121.00	−120.00	−117.00
Atl	Sand01	15	−127.00	−136.50	−135.00
Atl	Sand02	15	−127.00	−136.50	−135.00
Atl	Sand03	15	−127.00	−136.50	−135.00
Atl	Sand04	15	−127.00	−136.50	−135.00
Atl	Sand05	15	−127.00	−136.50	−135.00
Atl	Sand06	15	−127.00	−136.50	−135.00
Atl	Sand07	15	−127.00	−136.50	−135.00
Atl	Sand08	15	−127.00	−136.50	−135.00
Atl	Sand09	15	−127.00	−136.50	−135.00
Atl	Sand10	15	−127.00	−136.50	−135.00
Atl	SSa	15	−127.00	−136.50	−135.00
Atl	SSb	15	−127.00	−136.50	−135.00
Atl	SSc	15	−127.00	−136.50	−135.00
JCR	SS01	20	−150.00	−124.00	−110.00
JCR	SS04	15	−150.00	−124.00	−112.00
JCR	SS07	20	−150.00	−124.00	−112.00
JCR	SS10	20	−150.00	−124.00	−110.00
JCR	AP13	20	−150.00	−124.00	−110.00
JCR	AP16	20	−150.00	−124.00	−110.00
JCR	AP19	20	−152.00	−124.00	−110.00
KyM	SS03	20	−136.40	−136.40	−134.40
KyM	SS06	20	−147.40	−136.40	−138.10
KyM	SS09	20	−141.90	−136.80	−138.40
KyM	AP12	20	−147.00	−135.70	−135.10
KyM	AP15	20	−148.10	−136.20	−136.10
KyM	AP18	20	−147.40	−136.60	−136.80
KyM	SSI01	20	−140.90	−136.60	−134.40
KyM	SSI02	20	−138.90	−136.60	−133.40
KyM	SSI03	20	−144.90	−136.60	−133.40
KyM	SSI04	20	−141.90	−136.60	−135.40
KyM	SSI05	20	−144.90	−136.60	−134.40
KyM	SSI06	20	−146.90	−136.60	−135.40
KyM	SSI07	20	−149.90	−136.60	−135.40
KyM	SSI08	20	−152.90	−136.60	−135.40

Atl—*Atlantida*; JCR—*James Clark Ross*; KyM—*Kaiyo Maru*; Yuz—*Yuzhmorgeologiya*.

averaged together. Experimentation with bin size on selected echograms indicated little change in integrated energy attributed to krill when bin size is set larger than some minimal dimensions and smaller than very large regions of the echograms. Bin size was set at 5 m vertical dimension and 50 pings horizontal dimension (approximately 500 m at 2 s ping interval and 10 kn survey speed), but comparable results could have been obtained if the bin size was half or double these dimensions.

Following these procedures, S_V samples were adjusted for changes in assumed values for sound speed, absorption coefficients, and acoustic wavelengths; surface exclusion layers were set and adjusted where appropriate; bottom detection was verified and modified where appropriate; and reconstructed echograms were annotated to include in subsequent analyses only those data collected along the designated transects (excluded were data collected between transects, during station times, and within the period between local apparent sunset and local apparent sunrise). The echograms were then resampled; time-varied noise echograms were created and subtracted from the resampled echograms; for each transect the 38 kHz noise-free resampled echogram was then subtracted from the 120 kHz noise-free resampled echogram; and portions of the 120 kHz noise-free resampled echogram were masked to exclude regions where the difference between the mean volume backscattering strength at 120 and 38 kHz was less than 2 dB or greater than 16 dB. The masked noise-free resampled 120 kHz echogram was then integrated from the bottom of the surface exclusion layer to 500 m (2 m above the bottom if shallower than 500 m) and averaged over 1852 m (1 nm) horizontal distance intervals. The output from these analyses was a series of integrated backscattering areas attributed to krill (s_A), one value for each nm of acoustic transect, where s_A is expressed in units of m^2 of backscattering cross sectional area per square nm of sea surface area or Nautical Area Scattering Coefficient (NASC; MacLennan et al., 2002).

Conversion of integrated backscattering area attributed to krill to areal krill biomass density (ρ) was accomplished by applying a series of factors (C) equal to the quotient of the weight of an individual krill ($W(L)$) and its backscattering cross-sectional area ($\sigma(L)$) summed over the sampled body length (L) frequency distribution (Hewitt and Demer, 1993):

$$\rho = s_A C\left(\frac{g}{m^2}\right) \quad \text{where } C = \frac{W(L)}{\sigma(L)} \text{ and } L \text{ is expressed in mm.} \tag{2}$$

A weight-length relationship was derived from data collected aboard the *Kaiyo Maru* during the CCAMLR, 2000 Survey:

$$W(L) = 2.236 \times 10^{-6} L^{3.314}. \tag{3}$$

Backscattering cross-sectional area was derived from a definition of krill target strength (TS) as a function of L at 120 kHz adopted by CCAMLR in 1991 (CCAMLR, 1991, Annex 5, Paras 4.24–4.30), such that

$$\begin{aligned}\sigma(L) &= 4\pi 10^{\mathrm{TS}(L)/10} = 4\pi 10^{(-127.5+34.85\,\log(L))/10} \\ &= 4\pi 10^{-12.75} L^{3.485}.\end{aligned} \tag{4}$$

Substituting Eqs. (2) and (3) into (1), adjusting for units and summarizing over length frequency distribution:

$$C = 0.2917 \sum f_i(L)^{-0.171} \quad \text{where } \sum f_i = 1. \tag{5}$$

Cluster analysis performed on the net samples of krill collected over the CCAMLR, 2000 Survey area indicated three geographically distinct regions (Siegel et al., 2004). Small krill (1–2 yr, 26 mm modal length) were mapped in the eastern Scotia Sea in a broad tongue extending from the southern part of the survey area between the South Orkney and South Sandwich Islands north to the eastern end of South Georgia; very large krill (4–6 yr, 52 mm modal length) were mapped in the western Scotia Sea and Drake Passage; a third cluster of large krill (3–5 yr, 48 mm modal length, but also including several samples of intermediate size krill) was mapped in the inshore waters adjacent to the Antarctic Peninsula and extended across the northeastern part of the survey area (Fig. 2). Conversion factors for each of these clusters were calculated and are listed in Table 5. Transects were subdivided where they crossed cluster boundaries and s_A values from sections of the transects in each cluster were multiplied by the appropriate C in

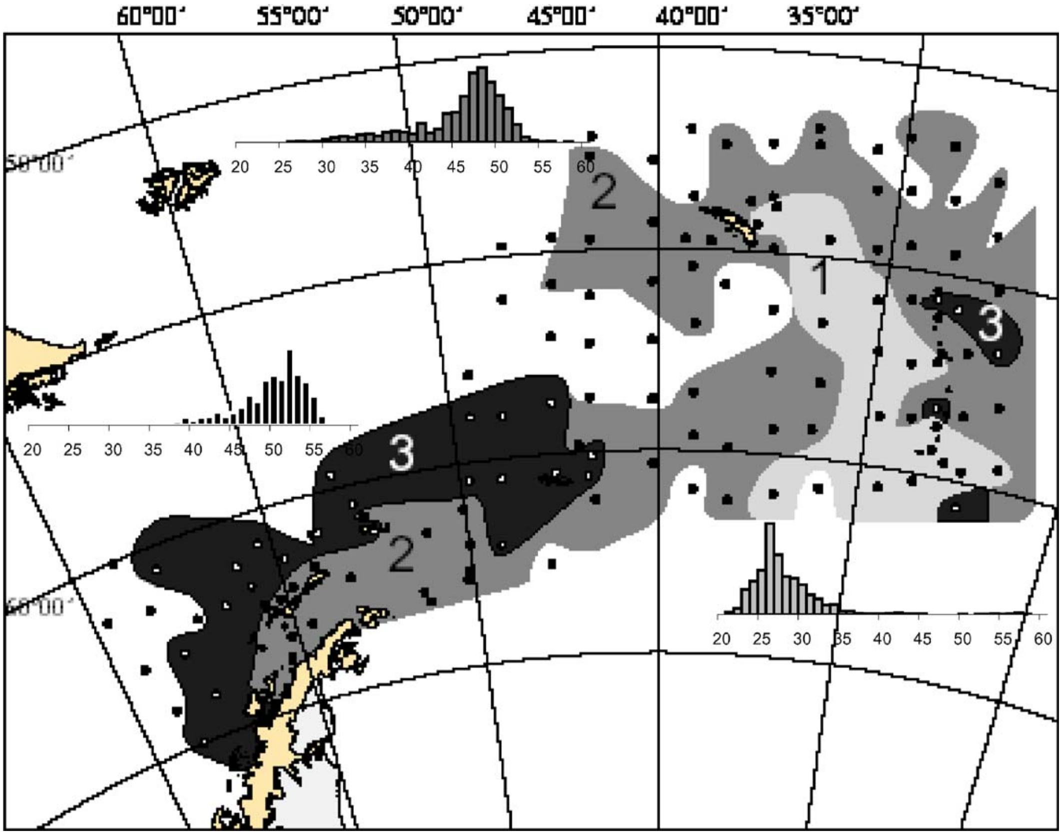

Fig. 2. Composite krill length-frequency distributions (length expressed in mm) and the spatial distribution of stations for each cluster (from Siegel et al., 2004).

Table 5
Factors for converting integrated backscattering area (s_A in units of m^2 of backscattering area per nm^2 of sea surface) to areal krill biomass density (ρ in units of $g\,m^{-2}$)

	Cluster 1	Cluster 2	Cluster 3	Clusters 2+3	Clusters 1+2+3
120 kHz	0.1636	0.1517	0.1477	0.1506	0.1560
38 kHz	0.5163	0.4786	0.4661	0.4753	0.4921
200 kHz	0.0982	0.0910	0.0886	0.0904	0.0936

Factors for 120 kHz were derived as explained in the text. Factors for 38 and 200 kHz were derived by evaluating the Greene et al. (1991) equation at these frequencies, where $TS_{38} = -132.44 + 34.85\log(L)$ and $TS_{200} = -125.23 + 34.85\log(L)$.

order to generate a series of areal krill biomass densities.

The mean density over each transect was assumed to be representative of the mean density of the stratum (Jolly and Hampton, 1990). The mean density of each stratum was thus calculated as the weighted average of all transects within each stratum, where the weighting was proportional to the length of each transect:

$$\bar{\rho}_k = \frac{1}{N_k}\sum_{j=1}^{N_k} w_j \bar{\rho}_j, \tag{6}$$

where $\bar{\rho}_k$ is the mean areal krill biomass density in the kth stratum, N_k is the number of transects in the kth stratum, and w_j is the normalized weighting factor for the jth transect as defined below, and $\bar{\rho}_j$ is the mean areal krill biomass density on the jth transect as defined below.

For several reasons ships deviated from the planned transects. Such deviations included random effects caused by strong winds and ocean currents, and larger systematic deviations caused by avoidance of icebergs. To correct for these larger deviations, an expected change in latitude per nautical mile of transect, ΔL, was calculated for each transect in the survey design. The actual latitude made good, $\Delta\hat{L}$, was derived by differencing the latitudes of the beginning and end of each interval. An interval weighting W_I was calculated as

$$W_I = \frac{|\Delta L| - |(\Delta L - \Delta\hat{L})|}{|\Delta L|} \tag{7}$$

If the deviation from the standard track line for a particular interval was greater than 10% (i.e., if $W_I < 0.9$), then the 1 nm integral was scaled by W_I, otherwise $W_I = 1$.

The sum of the interval weightings along each transect was used to weight the transect means to provide a stratum biomass, such that

$$L_j = \sum_{i=1}^{N_j} (W_I)_i, \tag{8}$$

where L_j is the length of the jth transect, $(W_I)_i$ is the interval weighting of the ith interval, and N_j is the number of intervals in the jth transect. The normalized weighting factor for the jth transect (w_j) was defined as

$$w_j = \frac{L_j}{(1/N_k)\Sigma_{j=1}^{N_k} L_j} \text{ such that } \sum_{j=1}^{N_k} w_j = N_k. \tag{9}$$

The mean areal krill biomass density over all intervals on the jth transect ($\bar{\rho}_j$) was defined as

$$\bar{\rho}_j = \frac{1}{L_j}\sum_{i=1}^{N_j} (s_A)_i (C)_i (W_I)_i, \tag{10}$$

where $(s_A)i$ is the integrated backscattering area for the ith interval and $(C)i$ is the conversion factor for the ith interval. Total biomass over the survey area was calculated as

$$B_0 = \sum_{k=1}^{N} A_k \bar{\rho}_k, \tag{11}$$

where A_k is the area of the kth stratum and N is the number of strata in the survey. Mean density over the survey area is thus calculated as

$$\bar{\rho} = \frac{\Sigma_{k=1}^{N} A_k \bar{\rho}_k}{\Sigma_{k=1}^{N} A_k}. \tag{12}$$

The variance of the mean areal krill biomass density in the kth stratum was calculated as a ratio estimator of variance as proposed by Jolly and Hampton (1990):

$$\begin{aligned}\mathrm{Var}(\bar{\rho}_k) &= \frac{N_k}{N_k - 1}\frac{\Sigma_{j=1}^{N_k} w_j^2 (\bar{\rho}_j - \bar{\rho}_k)^2}{(\Sigma_{j=1}^{N_k} w_j)^2} \\ &= \frac{\Sigma_{j=1}^{N_k} w_j^2 (\bar{\rho}_j - \bar{\rho}_k)^2}{N_k(N_k - 1)}.\end{aligned} \tag{13}$$

The contribution of the kth stratum to the overall survey variance of B_0 was defined as

$$(\mathrm{Var}(B_0))_k = A_K^2 \,\mathrm{Var}(\bar{\rho}_k) \tag{14}$$

so that the overall survey variance of the mean areal krill biomass density was calculated as

$$\mathrm{Var}(\bar{\rho}) = \frac{\Sigma_{k=1}^{N} (\mathrm{Var}(B_0))_k}{(\Sigma_{k=1}^{N} A_k)^2} \tag{15}$$

and the overall survey variance of B_0 was calculated as

$$\mathrm{Var}(B_0) = \sum_{k=1}^{N} (\mathrm{Var}(B_0))_k. \tag{16}$$

To generate a map of krill dispersion across the survey area, estimates of mean areal krill biomass density were interpolated onto a grid, of dimensions 2° of longitude by 1° of latitude, and the values contoured.

4. Results

Estimates of areal krill biomass density by transect, stratum, and survey are listed in Tables 6 and 7. Highest densities of krill were encountered in the mesoscale strata, ranging from $25.8\,\mathrm{g\,m^{-2}}$ (CV 26.4%) near the South Sandwich Islands to $150.4\,\mathrm{g\,m^{-2}}$ (CV 55.5%) near the South Orkney Islands; densities in the large-scale strata ranged from $11.2\,\mathrm{g\,m^{-2}}$ (CV 19.3%) off the Antarctic Peninsula to $24.54\,\mathrm{g\,m^{-2}}$ (CV 15.3%) in the western Scotia Sea; total krill biomass over the survey area was estimated at 44.3 million tonnes (CV 11.4%).

Although the densities of krill in the large-scale strata were generally low, the highest biomass of krill was estimated for the large-scale Scotia Sea strata (SS) due to the large area of this stratum (Table 7) coupled with the highest large-scale density. However, the highest biomass densities were mapped along the Scotia Ridge (Fig. 3), in areas where the fishery has operated in previous years (Fig. 1A). An area of moderately high krill biomass density was mapped to the south and east of South Georgia in water greater than 2000 m depth. This region coincides with that outlined for the cluster of small krill (Fig. 2). Approximately, two-thirds of the estimated krill biomass is located in areas where fishing has not occurred. Anecdotal evidence suggests that extensive fishing in the large-scale strata has not occurred because biomass densities are low and/or the location of fishable concentrations is not predictable.

There does not appear to be a coherent relationship between areas of elevated krill biomass density and the position of oceanic fronts (Brandon et al., 2004). This is consistent with the conclusions of Siegel et al. (2004) with regard to spatial patterns in the demography of krill sampled during the CCAMLR, 2000 Survey. More apparent was the association of moderate biomass densities with high numerical densities of small krill (Siegel et al., 2004) in a region with water mass affinities to the Weddell Sea (Brandon et al., 2004). Using flow models Murphy et al. (2004) predicted that these krill were under the pack ice in the northern Weddell Sea as recently as 2 weeks prior to the survey. Given the cold water intrusion into the area, the late retreat of sea ice in the vicinity, the identification of Weddell Sea water, and the distinct demographic patterns, Siegel et al. (2004) concluded that the high concentrations of juvenile krill in the eastern Scotia Sea were the result of an intrusion of krill from the south and represented a source of krill in the Weddell Sea distinct from the Bellingshausen Sea.

The estimate of B_0 and its associated variance derived from the CCAMLR, 2000 Survey were used to set γ at 0.091 (CCAMLR, 2000a, Annex 4, paras 2.96–2.113). The other life history parameters used in the population simulations are reprinted in Table 8. The precautionary yield (Y) for krill in the Scotia Sea, where $\gamma Y = B_0$, was set at 4 million tonnes.

5. Discussion

The estimates of krill biomass and its variance reported here are based on the assumption that the stratified random design proposed by Jolly and Hampton (1990) is appropriate. Alternatively, a geostatistical approach (Cressie, 1991) has been proposed for the design and analysis of acoustic surveys for aquatic organisms (Petitgas, 1993). While the application of geostatistics to acoustic surveys of fish has become widespread, few surveys of zooplankton have incorporated the approach. Murray (1996) compared geostatistical and random survey analyses as applied to three sets of acoustic survey data of Antarctic krill collected during the 1981 FIBEX survey and averaged over intervals ranging from 0.5 to 11.1 km. The datasets were highly skewed and little spatial structure was evident even after separately modeling the upper ends of the histograms. The geostatistically derived CVs for the data below the truncation point were less than that derived from random sampling theory for the full datasets; however, when combined with the variance estimates for the excluded portion of the data histogram no improvement in the CVs was observed. Murray (1996) concluded that the extreme skewness in the krill data, together with a lack of spatial pattern among the high values, presented problems for the application of geostatisics. However, Murray

Table 6
Mean areal krill biomass densities (ρ) and associated variances by transect and stratum

Transect						Stratum krill density		
Name	Length (nm) *8*	Weighting factor *9*	Krill density: Measured ($g\,m^{-2}$) *10*	Krill density: Weighted ($g\,m^{-2}$)	Variance component	Mean ($g\,m^{-2}$) *6*	Variance *13*	CV (%)
AP11	95.99	0.67	12.83	8.59	1.13	11.24	4.70	19.29
AP12	194.66	1.36	15.58	21.17	34.79			
AP13	133.00	0.93	11.79	10.94	0.26			
AP14	76.59	0.53	18.06	9.65	13.29			
AP15	108.14	0.75	22.88	17.27	77.18			
AP16	90.29	0.63	13.22	8.33	1.56			
AP17	156.60	1.09	10.57	11.55	0.54			
AP18	228.75	1.60	5.30	8.46	89.92			
AP19	205.40	1.43	3.61	5.18	119.59			
SS01	431.22	1.23	20.38	25.14	26.28	24.54	14.07	15.28
SS02	416.33	1.19	47.53	56.60	749.40			
SS03	364.24	1.04	26.11	27.19	2.66			
SS04	312.13	0.89	30.94	27.62	32.67			
SS05	397.78	1.14	25.49	29.00	1.17			
SS06	402.48	1.15	13.93	16.03	149.20			
SS07	379.43	1.09	30.16	32.73	37.17			
SS08	271.53	0.78	21.40	16.62	5.96			
SS09	346.36	0.99	10.43	10.33	195.34			
SS10	175.13	0.50	8.29	4.15	66.27			
SSA	326.60	1.07	8.18	8.75	11.29	11.32	23.10	42.46
SSB	199.88	0.65	1.97	1.29	37.44			
SSC	389.24	1.28	18.75	23.91	89.85			
SSI01	37.87	1.09	17.73	19.35	476.09	37.73	97.94	26.23
SSI02	35.11	1.01	27.65	27.96	103.96			
SSI03	38.34	1.10	61.30	67.71	677.62			
SSI04	28.67	0.83	14.48	11.96	368.57			
SSI05	31.56	0.91	25.83	23.48	117.00			
SSI06	32.88	0.95	29.89	28.32	55.08			
SSI07	35.14	1.01	95.76	96.94	3 451.40			
SSI08	38.13	1.10	23.78	26.12	234.93			
SOI01	38.71	1.22	12.20	14.93	28 615.52	150.37	6966.86	55.51
SOI02	32.65	1.03	221.61	228.84	5 412.21			
SOI03	29.61	0.94	361.59	338.62	39 127.21			
SOI04	25.51	0.81	23.65	19.08	10 447.39			
SG01	38.47	1.03	70.75	72.94	1 051.46	39.30	146.24	30.77
SG02	39.48	1.06	17.34	18.34	539.47			
SG03	39.07	1.05	42.35	44.34	10.24			
SG04	32.26	0.86	24.95	21.57	153.74			
Sand01	42.27	1.13	27.69	31.25	4.77	25.76	46.15	26.37
Sand02	38.89	1.04	20.88	21.69	25.60			
Sand03	38.35	1.02	20.89	21.39	24.83			
Sand04	36.60	0.98	22.11	21.60	12.72			
Sand05	39.33	1.05	18.09	19.00	64.81			
Sand06	36.28	0.97	85.63	82.94	3 363.21			
Sand07	27.21	0.73	28.11	20.42	2.93			
Sand08	37.09	0.99	10.47	10.37	229.21			
Sand09	39.57	1.06	6.86	7.24	398.80			
Sand10	38.96	1.04	20.83	21.67	26.23			

Italics indicate relevant equation. See also Appendix A for descriptions of labels and formulae.

Table 7
Mean areal krill biomass density (ρ) and standing stock (B_0), and associated variances, by stratum and for the entire survey

Stratum	Nominal area (km^2)	Mean density ($g\,m^{-2}$) Table 6	Area*Density (tonnes)	Variance component ($tonnes^2$) *14*
AP (11–19)	473,318	11.24	5,319,647.98	1,052,496,388,913.78
SS (01–10)	1,109,789	24.54	27,234 964.55	17,326,537,058,061.60
SS (A–C)	321,800	11.32	3,642,035.01	2,391,655,734,991,07
SSI (01–08)	48,654	37.73	1,835,720.49	231,845,632,004.71
SOI (01–04)	24,409	150.37	3,670,294.56	4,150,849,848,119.59
SG (01–04)	25,000	39.30	982,423.23	91,401,915,350.65
Sand (01–10)	62,274	25.76	1,603,985.17	178,954,989,453.98
Total	2,065,244		44,289,070.99	25,423,741,566,895.40
Survey				
Mean density *12*	21.44 $g\,m^{-2}$			
Variance *15*	5.96 $(g\,m^{-2})^2$			
CV	11.38%			
Krill standing stock *11*	44.29×10^6 tonnes			
Variance *16*	25 423 741.57 $\times 10^6$ $tonnes^2$			
CV	11.38%			

Relevant formula indicated by figures in italics. See also Appendix A for descriptions of labels and formulae.

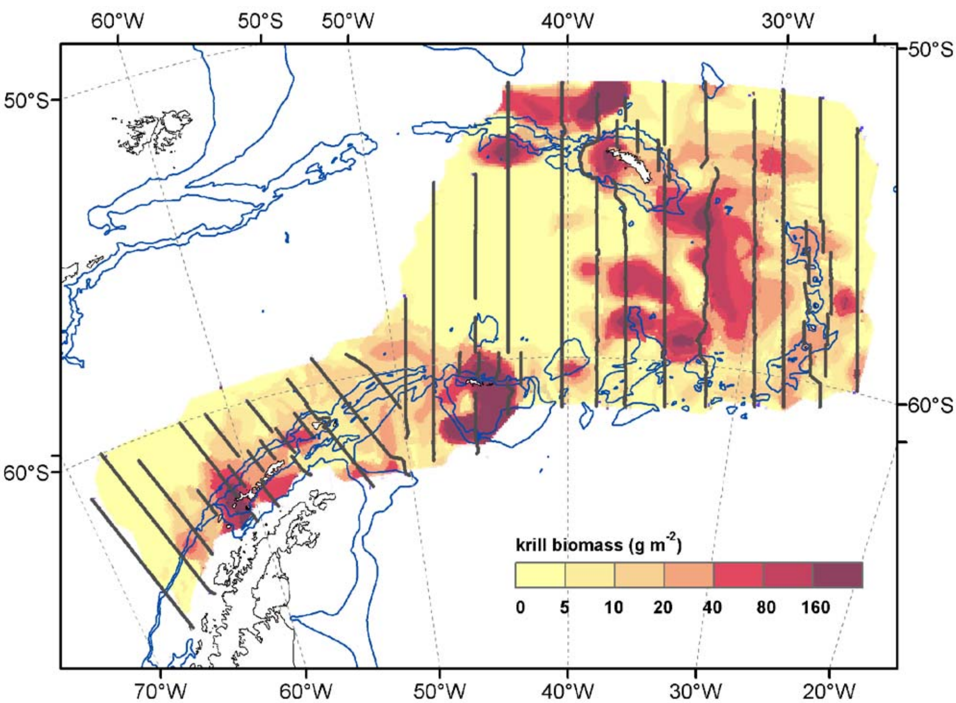

Fig. 3. Dispersion of krill biomass density over the survey area.

Table 8
Input parameters to the GYM for evaluating γ

Category	Parameter	Estimate
Age structure	Recruitment age	0
	Plus class accumulation	7
	Oldest age in initial structure	7
Recruitment (R) and natural mortality (M)	M and R dependent on proportion of recruits in stock where:	
	Proportion of recruits	0.557
	Standard deviation of proportion	0.126
	Age of recruitment class in proportion	2
	Data points to estimate proportion	17
von Bertalanffy growth	Time 0	0
	L_∞	60.8 mm
	K	0.45
	Proportion of year from beginning in which growth occurs	0.25
Weight at age	Weight–length parameter A	1.0
	Weight–length parameter B	3.0
Maturity	L_{m50}	32.0–37.0 mm
	Range: 0 to full maturity	6 mm
Spawning season		1 December–28 February
Estimate of B_0	Survey time	1 February
	CV	0.114
Simulation characteristics	Number of runs in simulation	1 001
	Depletion level	0.2
	Seed for random number generator	−24189
Characteristics of a trial	Years to remove initial age structure	1
	Observations to use in median S B_0	1 001
	Year prior to projection	1
	Reference start date in year	1 November
	Increments in year	365
	Years to project stock in simulation	20
	Reasonable upper bound for annual F	5.0
	Tolerance for finding F in each year	0.0001
Fishing mortality	Length, 50% recruited	30–39 mm
	Range over which recruitment occurs	9 mm
	Fishing selectivity with age	
Fishing season		1 December–1 March

(1996) also noted that considering entire transects as sampling units tended to smooth out smaller scale variations and underestimate the uncertainty associated with extremely high values. Geostatistical analysis of the data reported here was beyond the scope of this work but should be considered.

An analysis of the total uncertainty associated with the survey was undertaken by Demer (2004) who considered errors associated with system calibration, characterization of krill target strength, probability of detection, and the efficiency of algorithms used to delineate backscatter attributed to krill. Total error was evaluated by estimating krill biomass for each of the three frequencies used in the survey, assuming that the identified errors affect each of these estimates independently. Results from a Monte Carlo simulation of this process indicate that the mean of the total error distribution was not significantly different from the estimated sampling variability (i.e., the measurement variance would be negligible relative to the sampling variance if averaged over many surveys). Demer (2004) also considered potential biases and concluded that most were negligible or negative. An exception is species delineation where the algorithm used could not distinguish between small *E. superba* and other euphausiids (e.g. *Thysanoessa macrura*). More notable is the disparity observed in krill target strength predicted by an empirical model (Greene et al., 1991) versus a theoretical model (McGehee et al., 1998). The empirical model, where target strength is estimated as a function of body length, is used in the current analyses to convert integrated volume backscattering strength to krill biomass density. The theoretical model, where target strength is estimated as a function of body length, shape, curvature, orientation angle, and material properties, is impractical to apply under survey conditions because so many parameters must be characterized. One approach is to randomize the sound scattering process by assigning appropriate probability density functions to various parameter values and estimating a range of target strength values for various body lengths (Demer and Conti, 2003). The results of this and similar work will be improved estimates of krill target strength under natural conditions, which may provide a reason for re-evaluating the estimates of krill biomass density reported here.

The latest estimate of B_0 and its variance resulted in revised estimates of γ (0.091) and the precautionary yield of krill (4 million tonnes). Before the fishery can expand to this level, however, it will be necessary to establish mechanisms to avoid concentration of fishing effort near colonies of land-breeding krill predators. In the absence of detailed information regarding dispersion and movement of krill throughout their habitat, demand by krill predators, and variability in recruitment and the factors that control it, an earlier form of the yield model was adopted in order to establish the original precautionary yield (Butterworth et al., 1991, 1994). The current form of the model (now referred to as the Generalized Yield Model (GYM; Constable and de la Mare, 1996) still assumes a freely distributed krill population, homogeneously distributed predation pressure, and randomly determined recruitment. The effects of uncertainty with regard to input parameters are included, but spatial and temporal trends in krill demographics, predator demand, and fishing pressure are not. Several CCAMLR members are conducting research studies and long-term monitoring in order to provide some of this information (Agnew, 1997), but until a more complete management scheme is in place the GYM will remain the primary tool for regulating the fishery.

One approach to refining the management scheme is to modify the GYM so as to allow some of the input parameters to be spatially explicit. In this manner, spatial variations in predator demand, resulting in spatial variations in krill mortality, could be incorporated. Similar considerations could be made for recruitment and transport. The GYM would still treat the krill population in the Scotia Sea as a single stock, but allowances would be made for variability in population parameters across the region. Results from the CCAMLR, 2000 Survey suggest, however, that krill may be transported into the Scotia Sea from two sources (Brandon et al., 2004; Siegel et al., 2004; see also Watkins et al., 1999) and that the assumption of a single stock may be invalid.

A complementary approach, currently being investigated by CCAMLR, is the establishment of smaller management units (CCAMLR, 2001, paras 6.15–6.19). Constable and Nicol (2002) suggest that a first step in this approach could be to divide the larger subareas into non-overlapping land-breeding krill predator foraging areas. This was thought to be tractable because the principal archipelagoes, where breeding colonies of krill predators are located, are separated by distances larger than the predator foraging ranges. Information regarding predator foraging areas and prey demand would be complemented by information regarding the immigration and emigration of krill through the areas and information on the tactical behaviour of the fishery within these areas. These data then could be used to divide the precautionary yield among these smaller management units more rationally.

The establishment of smaller management units as a method for dispersing the harvest also assumes the existence of a single stock. However, monitoring within the units would allow for information feedback, and consequent adjustments to allocation of yield among the units as well as better characterization of input parameters to the population model. Identification and monitoring of key processes regulating the krill-centric ecosystem (Hewitt and Linen Low, 2000) would thus contribute to both the interim and the long-term goals of CCAMLR. Smaller management units may also be used in an experimental fashion. For example, certain units could be closed to fishing while the fishing level in other units may be allowed to approach γ (Constable and Nicol, 2002). Suitable monitoring schemes could be established to provide the data necessary to test key assumptions and predictions.

In the meantime, the GYM provides a method by which uncertainty in population parameter estimates can be explicitly incorporated into estimates of harvest rate. The framework is flexible and can accommodate restatement of management objectives and reformulation of the criteria used to ensure that the objectives are met. While the current criteria may be perceived as somewhat arbitrary they can be refined as new information is acquired regarding the relationships between krill population biomass, recruitment, and predator response. In addition, application of the GYM allows separation of the political process of setting management objectives and criteria from the technical process of operating the model and determining the harvest rate. However, use of the GYM to manage the krill fishery was adopted by CCAMLR as an interim measure to its preferred approach; that is, a feedback scheme whereby management measures are adjusted in response to ecosystem monitoring. The full development of this approach will require: (1) enhancement of the existing CCAMLR ecosystem monitoring program; (2) high-resolution, real-time information regarding the activities of fishing vessels; and (3) further development of models linking krill, their predators, environmental influences, and the fishery.

6. Deposition of data

Copies of all data files, including raw ping-by-ping echosounder output telegrams (EK5 files), echogram annotation files (EV files), various integration output files (CSV files), and summary tables (MS Excel files), are maintained at the CCAMLR Secretariat in Hobart, Australia. See *Rules for Access and Use of CCAMLR Data* available at: www.ccamlr.org.

Appendix A

Descriptors for labels in Tables 6 and 7, where i is used to index intervals along a transect, j is used to index transects within a stratum, and k is used to index strata.

Transect label	Formula/descriptor
Length	Transect length defined as the sum of all interval weightings $L_j = \sum_{i=1}^{N_j} (W_I)_i$ where L_j is the length of the jth transect, $(W_I)_i$ is the interval weighting of the ith interval, and N_j is the number of intervals in the jth transect.
Weighting factor	Normalized transect length $w_j = \dfrac{L_j}{\frac{1}{N_k}\sum_{j=1}^{N_k} L_j}$

Appendix A (*continued*)

Transect label	Formula/descriptor
	such that $\sum_{j=1}^{N_k} w_j = N_k$ where w_j is the weighting factor for the *j*th transect, and N_k is the number of transects in a stratum.
Krill density measured	Mean areal krill biomass density over all intervals on each transect $$\bar{\rho}_j = \frac{1}{L_j}\sum_{i=1}^{N_j}(s_A)_i(C)_i(W_I)_i$$ where $\bar{\rho}_j$ is the mean areal krill biomass density on the jth transect, $(s_A)_i$ is the integrated backscattering area for the *i*th interval and $(C)_i$ is the conversion factor for the *i*th interval.
Krill density weighted	Mean areal krill biomass density times the weighting factor $\bar{\rho}_{W_j} = w_j\bar{\rho}_j$ where $\bar{\rho}_{W_j}$ is the mean weighted areal krill biomass density on the *j*th transect.
Variance component	$$VarComp_j = w_j^2(\bar{\rho}_j - \bar{\rho}_k)^2$$ here $VarComp_j$ is the weighted contribution of the *j*th transect to the stratum variance.

Stratum label	Formula/descriptor
Mean	Stratum mean areal krill biomass density $$\bar{\rho}_k = \frac{1}{N_k}\sum_{j=1}^{N_k} w_j\bar{\rho}_j$$ where $\bar{\rho}_k$ is the mean areal krill biomass density in the *k*th stratum (after Eq. (1), Jolly and Hampton, 1990).
Variance	Stratum variance $$Var(\bar{\rho}_k) = \frac{N_k}{N_k-1}\frac{\sum_{j=1}^{N_k} w_j^2(\bar{\rho}_j-\bar{\rho}_k)^2}{\left(\sum_{j=1}^{N_k} w_j\right)^2} = \frac{\sum_{j=1}^{N_k} w_j^2(\bar{\rho}_j-\bar{\rho}_k)^2}{N_k(N_k-1)}$$ where $Var(\bar{\rho}_K)$ is the variance of the mean areal krill biomass density in the *k*th stratum.
CV (%)	Coefficient of variation $$\mathrm{CV}_k = 100\frac{(Var(\bar{\rho}_k))^{0.5}}{\bar{\rho}_k}$$ where CV_k is the coefficient of variation for the *k*th stratum.
Nominal area	Area of *k*th stratum (A_k) estimated at the time of survey design.
Mean density	Mean areal krill biomass density of the *k*th stratum, $\bar{\rho}_k$.

Appendix A (*continued*)

Stratum label	Formula/descriptor
Area*density	$A_k \bar{\rho}_k$
Variance component	$(Var(B_0))_k = A_k^2 Var(\bar{\rho}_k)$ where $(Var(B_0))_k$ is the contribution of the kth stratum to the overall survey variance of B_0.

Survey label	Formula/descriptor
Mean density	Overall survey mean areal krill biomass density $\bar{\rho} = \frac{\sum_{k=1}^{N} A_k \bar{\rho}_k}{\sum_{k=1}^{N} A_k}$ where N is the number of survey strata (after Eq. (2), Jolly and Hampton, 1990).
Variance	Overall survey variance of the mean areal krill biomass density $Var(\bar{\rho}) = \frac{\sum_{k=1}^{N} A_k^2 Var(\bar{\rho}_k)}{\left(\sum_{k=1}^{N} A_k\right)^2} = \frac{\sum_{k=1}^{N} (Var(B_0))_k}{\left(\sum_{k=1}^{N} A_k\right)^2}$ (after Eq. (3), Jolly and Hampton, 1990).
CV	Overall coefficient of variation of the mean areal krill biomass density $\mathrm{CV}_{\bar{\rho}} = 100 \frac{(Var(\bar{\rho}))^{0.5}}{\bar{\rho}}$
Krill Standing Stock	$B_0 = \sum_{k=1}^{N} A_k \bar{\rho}_k$
Variance	Overall survey variance of B_0 $Var(B_0) = \sum_{k=1}^{N} (Var(B_0))_k$
CV	Overall coefficient of variation of B_0 $\mathrm{CV}_{B_0} = 100 \frac{(Var(B_0))^{0.5}}{B_0}$

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